

Radiofrequency cascade readout of coupled spin qubits

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Silicon spin qubits based on metal–oxide–semiconductor (MOS) technology are compatible with semiconductor manufacturing and offer a route to scalable quantum processing. However, spin readout typically relies on proximal charge sensors, which add architectural complexity and limit qubit connectivity. In situ dispersive readout techniques are more compact, which can alleviate these constraints, but exhibit limited sensitivity. Here we report a radiofrequency electron-cascade readout method that enhances the dispersive signal through alternating-current electron co-tunnelling. With this approach, we achieve an enhancement in signal-to-noise ratio of more than 35 dB, leading to a minimum integration time of $7.6 \pm 0.2 \mu\text{s}$. We demonstrate singlet-triplet readout of two-electron spins in a natural silicon planar MOS quantum dot array, and coherent spin control using the exchange interaction, which forms the basis for entangling gates. We find dephasing times of up to 500 ns and a gate quality factor that exceeds 10.

Silicon-based quantum processors have been used to demonstrate high-fidelity qubit initialization^{1,2}, measurement^{3–5}, and single-^{6,7} and two-qubit control^{8–12} in small-scale devices of up to two qubits, with fidelities exceeding the 99% threshold required to implement quantum error correction¹³. Electron spin qubits in quantum dots (QDs) have also been used for simple instances of quantum error correction in a three-qubit array² and for the operation of a six-qubit processor¹⁴. Notably, such silicon-based quantum processors can be fabricated using industrial manufacturing techniques and integrated with cryogenic electronics^{15,16}, thus offering a promising route to scaled quantum computing¹⁷.

Spin qubits based on silicon metal–oxide–semiconductor (MOS) technology^{18,19} and Si/SiGe heterostructures^{10,14,20} are of interest for industrial manufacturing. The MOS approach shares similarities with modern silicon field-effect transistor manufacturing, which can be used to form MOS QDs in both planar devices^{11,18,19,21–23} and etched silicon

structures, such as nanowires^{4,24,25} and fin field-effect transistors^{26,27}. Although the latter constrains the qubit topology to $2 \times N$ bilinear QD arrays, the former offers easier scalability towards two-dimensional QD arrays²⁸, which are essential for implementing quantum error-correcting codes, such as the surface code¹³. Single-qubit performance in MOS devices fabricated using semiconductor manufacturing lines has been demonstrated^{24,27}, but quantum processors require two-qubit interactions to operate.

To enable further scaling, methods that simplify the readout infrastructure are required. The current standard for sensing—the radiofrequency (rf) single-electron transistor—provides high-fidelity readout^{3,5} at the cost of occupying substantial space on the qubit chip, which limits qubit connectivity. Fast and compact dispersive rf measurement techniques^{29–31} reduce the readout footprint. However, in situ dispersive readout metrics have seen limited progress in recent years³⁰.

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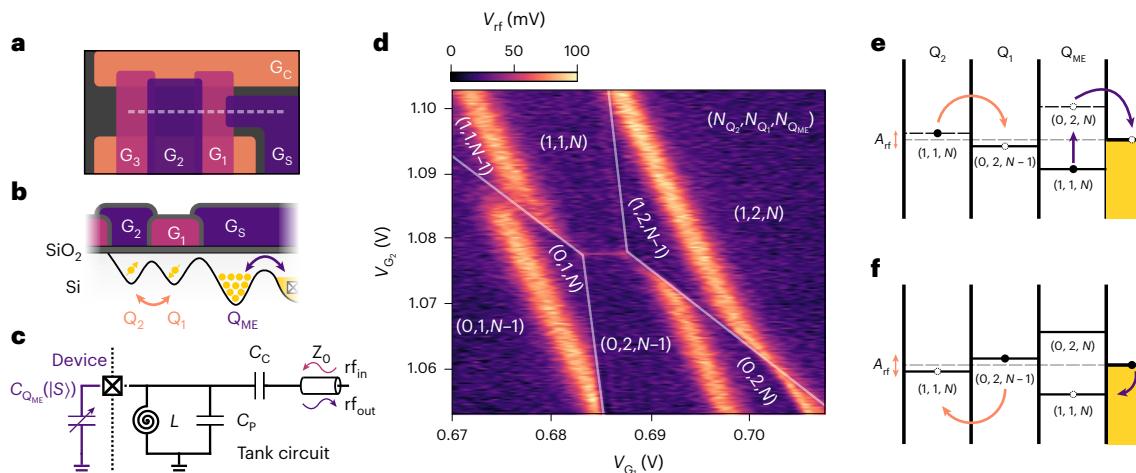


Fig. 1 | rf-driven electron cascade. **a, b**, Schematics of the top view (**a**) and cross section (**b**) (white dashed line in **a**) of the QD array. Gates G_1 and G_2 define the QDs Q_1 and Q_2 , which are tuned to the two-electron occupancy. The DQD is capacitively coupled to dot Q_{ME} , which is occupied by many electrons and is controlled by gate G_5 . Arrows indicate single-electron tunnelling events. **c**, Schematic of the rf resonator bonded to the ohmic contact of the device, including an equivalent circuit representation of the QD array as a spin-dependent variable capacitor $C_{QME}(S)$. The resonator is formed by an off-chip superconducting spiral inductor $L = 136$ nH arranged in parallel with the parasitic capacitance $C_p = 0.4$ pF of the assembly. Connected to the transmission line Z_0 via

a coupling capacitor $C_c = 0.1$ pF, $rf_{in(out)}$ represents the incident (reflected) rf signal on the resonator. **d**, Charge stability diagram of the DQD as a function of gate voltages V_{G1} and V_{G2} . V_{rf} denotes the demodulated rf voltage. **e, f**, Schematic representations of the cascade process in which an rf excitation with amplitude A_{rf} synchronously drives charge transitions within the QD array. The reservoir is shown as the shaded region, and the dashed lines mark its Fermi level. **e**, A change in the charge occupation from $(N_{Q2}, N_{Q1}, N_{QME}) = (1, 1, N)$ to $(0, 2, N-1)$ raises the electrochemical potential of the Q_{ME} above the Fermi level, causing one electron to synchronously escape to the reservoir. **f**, When the DQD is driven back to $(1, 1, N)$, an electron tunnels back from the reservoir to Q_{ME} .

In this Article, we describe an in situ dispersive sensing mechanism, termed the rf electron cascade, that offers high spin qubit readout sensitivity and is demonstrated here in a planar silicon double quantum dot (DQD) device. With the readout method, we achieve a minimum integration time of 7.6 ± 0.2 μ s, and using a physical model³², we calculate a $67 \pm 1\%$ singlet-triplet readout fidelity limited by spin relaxation. The measurement rate reported here represents an improvement of over two orders of magnitude compared with state-of-the-art results on dispersive readout in planar MOS devices³⁰. We also demonstrate control of an exchange-mediated coherent interaction, which forms the basis for a $\sqrt{\text{SWAP}}$ gate between two spin qubits.

rf electron-cascade readout

Reading out spin qubits within semiconductor QDs typically involves mapping a spin state of interest onto a charge state of one or more QDs^{33,34}, which can then be detected using a variety of charge-sensing methods³⁵. For example, the Pauli spin blockade (PSB) can be used to map the singlet and triplet states of a pair of spin qubits onto two different charge configurations of a DQD (for example $(1, 1)$ or $(0, 2)$), which are then detected by a single-electron transistor³⁶ or single-electron box⁴. In situ dispersive readout of a DQD combines these into a single step, using the PSB to directly distinguish between singlet and triplet states through their difference in the alternating current (a.c.) polarizability³⁷. This difference in polarizability is detected by incorporating the DQD into an rf tank circuit and measuring changes in the reflected rf signal. However, in situ dispersive readout has suffered from low sensitivity in planar MOS silicon quantum devices due to the relatively low gate lever arms³⁰. To improve the sensitivity of this technique, we introduce a third QD coupled to a charge reservoir, which acts as an amplifier in measuring the a.c. polarizability of the DQD. Instead of measuring the usual single-electron a.c. generated by cyclic tunnelling between the two-spin singlet states of the DQD³⁵, we leverage the synchronized single-electron a.c. current at the third dot-reservoir system generated as a consequence of the strong capacitive coupling to the DQD. Our approach offers the benefit of charge-enhancement techniques such as latching³⁸, direct current (d.c.) cascading³⁹ and spin-polarized single-electron boxes²⁵ while retaining the non-demolition nature of in situ dispersive readout methods⁴⁰.

We use a device based on planar silicon MOS technology with an overlapping gate design⁴¹ (Fig. 1a,b, Methods and Supplementary Section 1). QDs Q_1 and Q_2 form a DQD, which we tune to hold two electrons, while Q_2 is capacitively coupled to a multi-electron QD (Q_{ME}) that can exchange electrons with a charge reservoir. To measure the charge state of the system, we connect a superconducting spiral inductor to the reservoir to form an LC resonator (Fig. 1c). At voltages where the charge in Q_{ME} is bistable, cyclic tunnelling between the small rf signal supplied to the resonator produces a change in capacitance that can be detected as a change in the phase response $\Delta\Phi$ or demodulated voltage V_{rf} using homodyne techniques³⁵. Lines in the gate voltage space showing the Q_{ME} charge bistability are shifted when they intersect charge transitions of the DQD, as shown in Fig. 1d. Such shifts form the basis of dispersive charge-sensing measurements^{4,42}, which we do not exploit here.

Instead, we focus on the directly observable a.c. signal in the region of the gate voltage space where charge transitions can occur between Q_1 and Q_2 . We ascribe this signal to a two-electron charge cascade effect driven by the rf excitation, which we explain using the diagrams in Fig. 1e,f. Consider an rf cycle in which the system starts in the occupation configuration $(N_{Q1}, N_{Q2}, N_{QME}) = (1, 1, N)$. Owing to the strong capacitive coupling between Q_2 and Q_{ME} , the rf excitation that drives the DQD from the $(1, 1)$ to the $(0, 2)$ state synchronously forces an electron out of Q_{ME} in a cascaded manner, leading to $(0, 2, N-1)$. The second half of the rf cycle then reverses the process. Overall, the rf cascade measures the polarizability of the DQD system, as for in situ dispersive readout measurements^{30,31}, but with the substantial advantage that the induced charge can be much greater, resulting in a dispersive measurement with greater sensitivity (see Supplementary Section 2 for more discussion on the requirements for rf electron-cascade readout).

Specifically, we find the power signal is amplified in the cascade approach compared with direct dispersive readout, by a factor

$$A = \left(1 + \frac{1 - \alpha_{R,ME}}{\alpha_{R,2} - \alpha_{R,1}}\right)^2 > 1, \quad (1)$$

where $\alpha_{R,j}$ represents the gate lever arm between the reservoir and QD j . In particular, the sensor detects not only the interdot gate

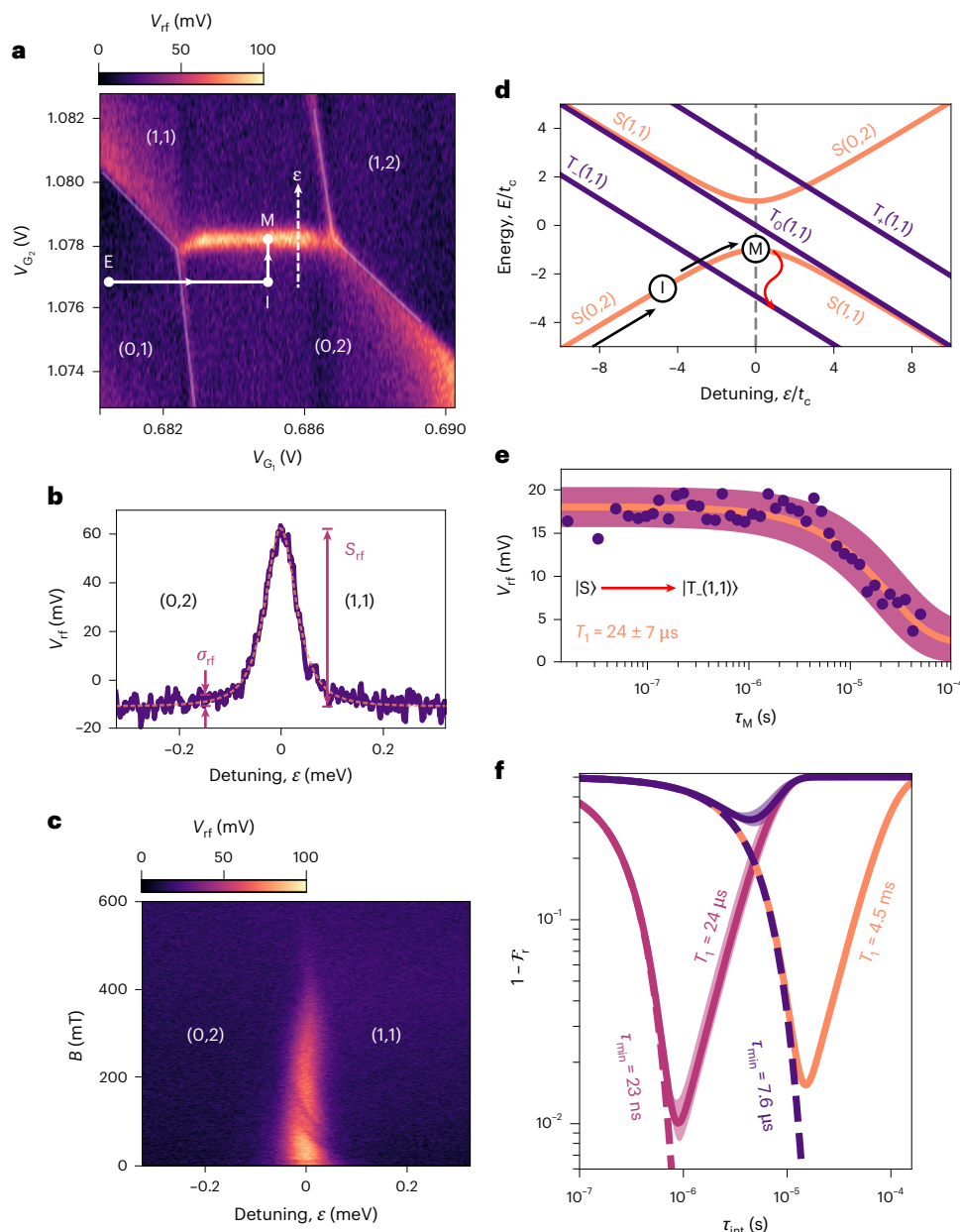


Fig. 2 | rf-cascade singlet-triplet readout. a, Charge stability diagram of the DQD around the (1, 1)–(0, 2) interdot charge transition, with a voltage pulse sequence (white arrows) and detuning axis ε overlaid. V_{rf} denotes the demodulated rf voltage. **b**, V_{rf} as a function of detuning across the interdot charge transition around $\varepsilon = 0$, fitted with equation (4) (dashed orange line). S_{rf} and σ_{rf} represent the signal amplitude and standard deviation, respectively. **c**, Magneto-spectroscopy of the interdot charge transition as a function of applied magnetic field B and ε . **d**, Energy diagram showing the dependence of the two-electron spin states, singlet (S) and triplet (T), as a function of ε with respect to the interdot tunnel-coupling t_c . The pulse sequence depicts the initialization

(I) of $|S(0, 2)\rangle$ via an adiabatic ramp from the (0, 1) empty (E) state, followed by a non-adiabatic pulse to $\varepsilon = 0$ for measurement (M). **e**, V_{rf} as a function of wait time τ_M at $\varepsilon = 0$ before measurement, following the pulse sequence depicted in **a** and **d**. The fitted line indicates a $|S\rangle$ to $|T_-(1, 1)\rangle$ relaxation time $T_1 = 24 \mu\text{s}$. **f**, Calculated readout infidelity $1 - F_r$ as a function of integration time τ_{int} as described by equation (7). Solid lines depict the fidelity with a limited relaxation time T_1 , whereas dashed lines depict it for $T_1 = \infty$. Parameters used from left to right: $\tau_{min} = \{23 \text{ ns}, 7.6 \mu\text{s}, 7.6 \mu\text{s}\}$ and $T_1 = \{24 \mu\text{s}, 24 \mu\text{s}, 4.5 \text{ ms}\}$. In both **e** and **f**, shaded areas indicate the propagated error from the ± 1 standard deviation of the fitted parameters.

polarization charge $(\alpha_{R,1} - \alpha_{R,2})e$, where e is the charge on an electron, but also the cascaded charge collected at the reservoir, $(1 - \alpha_{R,ME})e$ (see Supplementary Section 3 for a derivation). By comparing the measured signal-to-noise ratio (SNR) with and without the cascade effect, we find a lower bound for the power amplification factor, $A \geq (3.4 \pm 0.1) \times 10^3$ (+35.4 dB). The cascade SNR is extracted from the fit for the interdot charge transition shown in Fig. 2a,b (equations (4) and (5)). If the cascade is absent, the SNR is assumed to be upper bounded by ≤ 0.5 , as there is no observable signal, as shown in Extended Data Fig. 1a,e. From the cascade SNR, we extract a minimum integration time of

$\tau_{min} = 7.6 \pm 0.2 \mu\text{s}$ (equation (6)), which is an improvement of over two orders of magnitude compared with previous planar MOS demonstrations of in situ dispersive readout³⁰.

We use the rf cascade to distinguish between the singlet and triplet states of the DQD via the PSB. The signature of the PSB can be observed by measuring the asymmetric disappearance of the interdot charge transitions as the applied magnetic field is increased³⁷, as shown in Fig. 2c. At low magnetic field ($B \leq 200 \text{ mT}$), the system is free to oscillate between singlet states ($|S(1, 1)\rangle \leftrightarrow |S(0, 2)\rangle$) due to the action of the rf drive, yielding a signal in the rf response. However, at higher fields ($B \geq 200 \text{ mT}$),

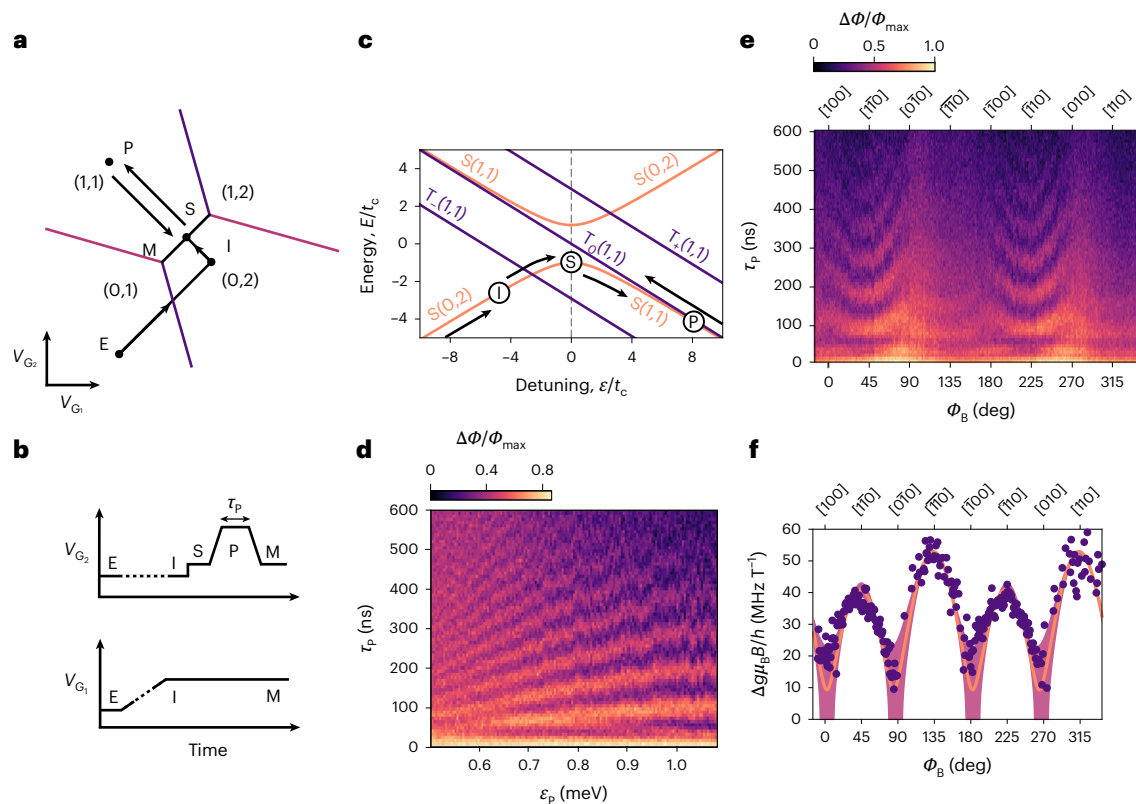


Fig. 3 | Measurement of the SOI. **a**, Schematic of the DQD charge stability diagram around the (1,1)–(0,2) interdot charge transition with voltage pulse sequence EISPM overlaid (see Methods). **b**, The pulse sequence shown as a function of time. The dashed lines indicate longer durations. **c**, Energy diagram showing the dependence of the two-electron spin states, singlet $|S\rangle$ and triplet $|T\rangle$, as a function of detuning ϵ with respect to the interdot tunnel-coupling t_c . **d**, $|S\rangle$ – $|T_0\rangle$ oscillations as a function of duration τ_P and detuning at point P, ϵ_P , in the pulse sequence (applied magnetic field $B = 250$ mT and in-plane magnetic field

orientation $\phi_B = 235^\circ$). **e**, $|S\rangle$ – $|T_0\rangle$ oscillation frequency dependence as a function of ϕ_B , measured as changes in rf phase with respect to a global maximal phase $\Phi_{\max}$ (a fixed detuning of $\epsilon_P = 0.926$ meV is used). The oscillation frequencies were obtained from a Fourier analysis. **f**, The SOI component of the extracted frequencies, $\Delta g\mu_B B/h$, was fitted (line) using the model described in equation (2). Here Δg is the difference in g factors between QDs, μ_B is the Bohr magneton, B is the applied magnetic field and h is Planck's constant. The shaded area shows the propagated error from the ± 1 standard deviation of the fitted parameters.

the polarized triplet $|T_-(1,1)\rangle$ state becomes the ground state for $\epsilon \geq 0$ (Fig. 2d), which prevents a charge transition and results in the disappearance of the signal, initially for the region of the transition closer to the (1,1) charge configuration. A quantum capacitance-based simulation of the data shown in Fig. 2c indicates an interdot tunnel-coupling of $t_c = 2.4$ GHz and electron temperature $T_e = 50$ mK (Supplementary Section 5). Figure 2e shows the decay from $|S\rangle$ to $|T_-(1,1)\rangle$ at $\epsilon = 0$ for applied magnetic field $B = 250$ mT. The corresponding relaxation time $T_1 = 24 \pm 7$ μ s, which is consistent with a study of a similar device, where a relaxation time of $T_1 = 10$ μ s was observed near zero detuning for a comparable tunnel-coupling ($t_c \geq 1.9$ GHz)⁴³. In that study, T_1 was found to vary exponentially with t_c , with relaxation times exceeding 100 ms for $t_c < 1$ GHz. Lowering t_c would also enhance the readout sensitivity, as the dispersive signal is maximized at $2t_c = f_{\text{rf}}$ (ref. 44), where f_{rf} is the resonator drive frequency, which we set to 512 MHz.

We assess the performance of the rf-driven electron cascade by calculating the readout fidelity $\mathcal{F}_r$ as a function of integration time using equation (7)³². We calculate a relaxation-limited readout fidelity of $\mathcal{F}_r = 67 \pm 1\%$ based on the experimentally obtained $\tau_{\min} = 7.6$ μ s and integration time $\tau_{\text{int}} = 8$ μ s. The corresponding readout infidelity $1 - \mathcal{F}_r$ is depicted in Fig. 2f (dark purple line). This infidelity is comparable to previous in situ readout demonstrations but was achieved with integration times that are 1–2 orders of magnitude faster than those reported in previous silicon planar MOS and implanted donor systems^{29,30} (Supplementary Section 7). To achieve 99% fidelity, two strategies are indicated in Fig. 2f: (1) Reduce the minimum integration time to 24 ns (light purple line) by enhancing the SNR through

resonator optimization, quantum-limited amplification or both^{35,45}. (2) Extend the relaxation time of the system, which for the $T_1 = 4.5$ ms reported in ref. 30 yields the orange line.

We highlight that, unlike other charge-enhancement techniques^{25,38,39}, the rf electron cascade retains the non-demolition nature of in situ dispersive readout measurements, as the DQD system remains in an eigenstate after a measurement is performed^{1,46}. We note that the rf excitation is continuously applied for all measurements in this Article, and we discuss the potential impact of this in the section ‘Echo sequence’.

Characterizing the spin–orbit coupling

Having established a method that distinguishes between singlet and triplet spin states, our goal is to prepare and coherently control spin states of the DQD through voltage pulses along the detuning axis, ϵ . Such pulses bring the DQD: (1) from the (0,2) charge configuration in which a singlet is prepared, (2) into the (1,1) region where the electron spins are spatially separated between QDs and may evolve, and (3) back to an intermediate point where they can be measured (Fig. 3a–c). Deep in the (1,1) region, the spin basis states are predominantly $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$. Under an adiabatic ramp to $\epsilon = 0$ for readout, these two states map onto the $|T_0(1,1)\rangle$ and $|S(0,2)\rangle$ states, respectively. The basis states are separated in energy by $\hbar\Omega = \sqrt{J(\epsilon)^2 + \Delta E_z^2}$, where we include the kinetic exchange interaction $J(\epsilon)$ and the Zeeman energy difference between electrons in each dot ΔE_z . The spin detuning $\Delta E_z = \Delta g\mu_B B + g\mu_B \Delta B_{\text{HF}}$ (where μ_B is the Bohr magneton and h is Planck's constant) contains two main contributions: (1) the difference in g factor between QDs $\Delta g = |g_2 - g_1|$

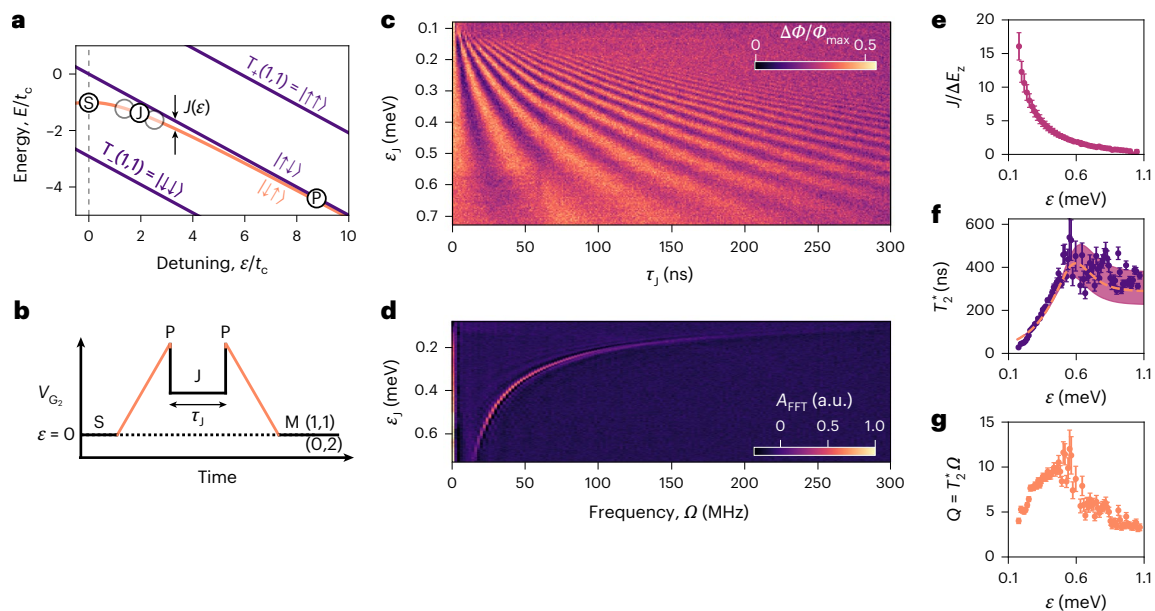


Fig. 4 | Exchange control in a natural-Si DQD device. a, Energy diagram depicting two-electron spin states in the (1,1) detuning ε regime, with pulse sequence steps overlaid. Each axis is plotted with respect to the interdot tunnel-coupling t_c . **b**, Detuning pulse sequence including initialization (P) to the $|\downarrow\uparrow\rangle$ state via a semi-adiabatic ramp (orange), followed by a non-adiabatic pulse (J) to near zero detuning to increase the exchange coupling $J(\varepsilon)$ for duration τ_j . **c**, Exchange-driven oscillations between the $|\downarrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle$ states. The measured rf-phase response is proportional to the singlet probability. **d**, The corresponding fast Fourier transform amplitude A_{FFT} . **e**, Ratio between exchange coupling

strength $J(\varepsilon)$ and dot-to-dot Zeeman energy difference ΔE_z . **f**, Dephasing time T_2^* (purple dots) extracted from the decay of the exchange oscillations and fitted with $T_2^* = \sqrt{2\hbar/\delta}(\hbar\Omega)$ (orange dashed line)^{49,54}. The shaded area shows the propagated error from the ± 1 standard deviation of the fitted parameters. **g**, Qubit quality factor $Q = T_2^*\Omega$. In **e** and **g**, each data point was extracted as a fitted parameter at a fixed detuning ε_j point of **c**. The dataset for each fit consists of around 300 points obtained from over 64×10^3 averages. Each error bar represents the standard deviation of a fitted parameter.

arising from variations in the spin–orbit interaction (SOI) near the Si/SiO₂ interface^{22,47,48} and (2) the difference in the effective ²⁹Si nuclear magnetic field experienced by each QD, ΔB_{HF} . The random fluctuations in the effective magnetic field experienced by each electron in the DQD can be described by a normal distribution with mean of 0 (given the negligible spin polarization) and standard deviation $\sigma_{\text{HF}} = 30 \pm 4 \mu\text{T}$, as we shall see later. This value corresponds to a hyperfine energy strength of $3.4 \pm 0.4 \text{ neV}$, which aligns well with other reports for natural silicon^{20,49–51}.

In previous work, the spin detuning ΔE_z was leveraged to drive oscillations between the $|S\rangle$ and $|T_0\rangle$ states^{22,23,51,52}. At an applied magnetic field $B = 250 \text{ mT}$, we observe similar oscillations using the pulse sequence presented in Fig. 3a–c. We start in the (0,1) configuration by emptying dot Q₁, then initialize the $|S(0,2)\rangle$ state via an adiabatic ramp across the (0,1)–(0,2) charge transition. A fast non-adiabatic pulse to ε_p in the (1,1) region leads to oscillations between $|S\rangle$ and $|T_0\rangle$ over the dwell time τ_p . The final state is then measured dispersively using a non-adiabatic pulse back to the (1,1)–(0,2) charge transition at $\varepsilon = 0$ for readout. The $|S\rangle$ to $|T_0\rangle$ oscillations shown in Fig. 3d provide a direct measurement of Ω . For $\varepsilon_p \gtrsim 0.9 \text{ meV}$, the dependence of the oscillation frequency on detuning is substantially reduced, indicating that, in this region, the ΔE_z term dominates ($J(\varepsilon) \leq \Delta E_z$), as Δg is only weakly dependent on the detuning ($\partial \Delta g / \partial \varepsilon \approx 0$)^{23,52}. As we shall see later, at the deepest detuning ($\varepsilon_p = 1.054 \text{ meV}$), we find $J/\Delta E_z = 0.5 \pm 0.3$.

The strength of the SOI means that the Δg term depends on Rashba and Dresselhaus spin–orbit couplings. The SOI (and, hence, Δg) can be tuned by varying the electrostatic confinement perpendicular to the interface and the transverse magnetic field^{22,47}. We vary the orientation of the in-plane magnetic field and observe changes in the $|S\rangle$ – $|T_0\rangle$ oscillation frequency, as shown in Fig. 3e,f. We fit the variation in Ω as a function of the angle ϕ_B between the [100] crystal axis and the applied (in-plane) magnetic field²²,

$$\Delta E_z/h = \sqrt{(|B| |\Delta\alpha - \Delta\beta \sin(2\phi_B)|)^2 + (g\mu_B\sigma_{\text{HF}}/h)^2}. \quad (2)$$

The Rashba and Dresselhaus SOI terms are, respectively, captured by $\Delta\alpha$ and $\Delta\beta$. We find $\Delta\alpha = 6.2^{+1.6}_{-1.5} \text{ MHz T}^{-1}$ and $\Delta\beta = 45^{+5}_{-7} \text{ MHz T}^{-1}$, which are larger than other reported values^{22,48,53} and could be partially influenced by the large asymmetry in the gate biasing conditions. The fit assumes that for the fixed detuning $\varepsilon_p = 0.926 \text{ meV}$ used here, the residual exchange interaction $J(\varepsilon_p)/h = 6.3 \pm 1.9 \text{ MHz}$ is independent of the in-plane magnetic field orientation. In the following sections we operate at an in-plane magnetic field direction near the $[\bar{1}\bar{1}0]$ direction at $\phi_B = 55^\circ$ (235°). Overall, this section expands the recent studies of the SOI in isotopically purified ²⁸Si MOS nanostructures^{22,23,48,53} to natural silicon, where the non-negligible effect of the Overhauser field needs to be taken into account.

Exchange control

We implement exchange control using the sequence depicted in Fig. 4a,b, where the $|\downarrow\uparrow\rangle$ state is initialized via a ramp from $\varepsilon = 0$ into the (1,1) configuration, which is adiabatic with respect to E_z (ref. 20). A fast non-adiabatic pulse towards zero detuning increases the exchange coupling, driving oscillations between the $|\downarrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle$ states at frequency $\Omega(\varepsilon)$, as observed in Fig. 4c. The final state after some evolution time τ_j is projected to $|S\rangle$ or $|T_0\rangle$ for readout. The Fourier transform of the exchange oscillations (Fig. 4d) reveals a single peak with increasing frequency as the detuning is reduced, indicating the purity of the oscillations and the enhanced exchange strength at lower detuning. From this, we observe that the exchange coupling is tunable over a range of $J = 5$ –122 MHz.

To quantify the properties of these rotations, we combine the results of the exchange oscillations in Fig. 4c and the $|S\rangle$ – $|T_0\rangle$ oscillations in Fig. 3d, to extract the ratio $J/\Delta E_z$ and the intrinsic coherence

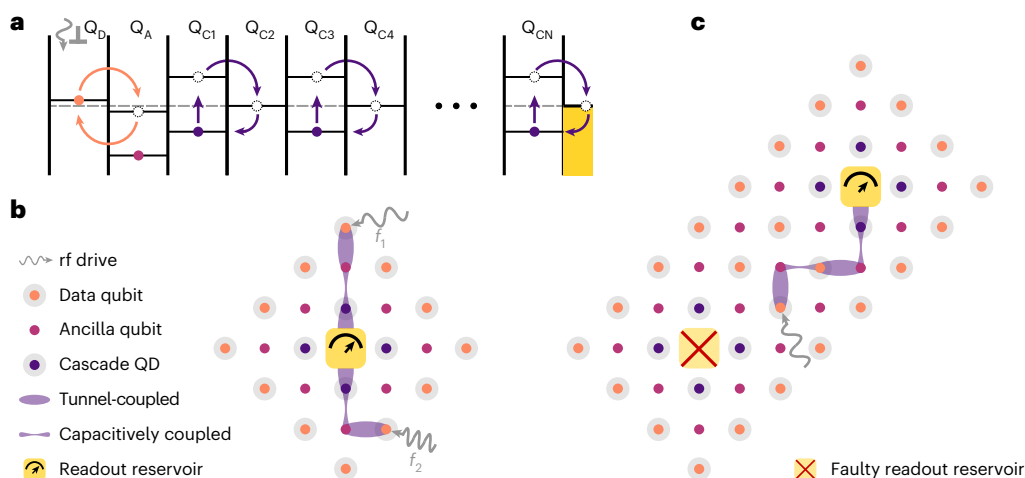


Fig. 6 | Extending the rf-cascade readout to two-dimensional arrays.

a, Schematic representation of the cascade process extended to an arbitrarily long one-dimensional array. Readout of the PSB is achieved by tunnel-coupling the data qubit Q_D (orange) and ancilla qubit Q_A (light purple). The resulting DQD is capacitively coupled to a chain of DQDs tuned into the cascade configuration (Q_{CN}) (dark purple), which enables in situ dispersive readout at an arbitrary distance. **b**, Schematic of a two-dimensional array of unit cells centred around a

readout reservoir (yellow) and connected to an rf reflectometry readout apparatus. Simultaneous multiplexed readout is achieved by applying distinct rf frequencies f_1 and f_2 to separate electrostatic gates, each controlling data qubit QDs driving distinct cascaded charge transitions. **c**, Repetition of the unit cell highlighting the robustness of the scheme to points of failure, such as a faulty readout reservoir, by rerouting the readout cascade chain to the nearest reservoir.

effect of the rf readout excitation, which is active throughout the control sequence. We estimate the upper bound on detuning fluctuations associated with this rf excitation to be $\delta\epsilon_{\text{rms}}^{\text{rf}} \leq 2.7 \mu\text{eV}$ (equation (8)). However, this limitation is not intrinsic to the readout scheme itself, as the effect can be effectively mitigated by implementing a pulsed readout protocol. In this approach, the rf drive is deactivated during the control sequence and activated only during the readout phase.

Conclusions

We have described rf electron-cascade readout, a high-gain in situ dispersive readout technique that we demonstrated here in a planar MOS device. The rf-driven electron cascade could be extended to larger arrays for distant readout, which would eliminate the need for swap-based schemes that rely on shuttling information to a sensor⁵⁹. Such an extension builds upon existing schemes for two-dimensional grids using data and ancilla qubits (Fig. 6)^{4,13}. We assume that the tunnel barriers between each QD can be precisely controlled to enable optimal readout fidelity through tuning t_c (ref. 5).

Figure 6a illustrates the readout protocol in a simplified one-dimensional array. To readout the data qubit Q_D at the periphery of the unit cell, the data qubit is tunnel-coupled to a neighbouring ancilla qubit Q_A . The ancilla qubit, in turn, is capacitively coupled to a chain of DQDs configured in the cascade configuration and eventually connected to a reservoir. An rf drive applied to the ancilla-data DQD initiates the cascade, which propagates along the chain to a readout reservoir. This scheme uniquely enables the simultaneous readout of distant data qubits through frequency multiplexing at the readout tank circuit. By driving several cascade chains at distinct frequencies, several distant qubits can be read out simultaneously (Fig. 6b), in contrast to earlier schemes³⁹. Furthermore, combining unit cells into a dense, scalable two-dimensional grid allows the readout to share resources, resulting in the system being resilient to failure points, such as faulty QDs or reservoirs (Fig. 6c).

Furthermore, we have demonstrated exchange control, which forms the basis for two-qubit gates between spin qubits, in a natural planar silicon MOS DQD device. The measured detuning noise is comparable with that of other planar MOSs⁵⁵, and the T_2^* is relatively long for a natural silicon device⁵⁸. These results are consistent with reports on devices from the same 300-mm fabrication line³⁵, indicating that

process quality is a contributing factor. Follow-up studies could include measurements in isotopically enriched Si samples¹² (Supplementary Section 10). Further work could also extend exchange control to larger spin qubit arrays by adapting dedicated gates^{11,19} to primarily control the exchange strength over a wider range. This could enable symmetric exchange pulses and reduce $J/\Delta E_z$ to well below 1, which should lead to an overall reduction in sensitivity to charge noise.

Methods

Fabrication details

The device measured in this study was fabricated on a natural silicon 300-mm wafer, with three 30-nm-thick in situ n^+ phosphorus-doped polycrystalline silicon gate layers formed with a wafer-level electron-beam patterning process^{41,55}. We used a high-resistivity ($>3 \text{ k}\Omega \text{ cm}^{-1}$) p-type Si wafer. First, an 8-nm-thick, high-quality SiO_2 layer was grown thermally to minimize the density of defects in the oxide and at the interface. Then, we subsequently patterned the gate layers using litho-etch processes and electrically isolated them from one another with a 5-nm-thick blocking high-temperature-deposited SiO_2 layer (ref. 41). We employed the first layer of gates (closest to the silicon substrate) to provide in-plane lateral confinement in the direction perpendicular to the DQD axis. We used the second layer of gates (G_2 in this case) to form and control primarily QD Q_2 . Finally, we used the third gate layer to form and control QD Q_1 via G_1 and both the multi-electron QD Q_{ME} and reservoir via G_s , as shown in Fig. 1a,b. Supplementary Section 1 includes scanning and transmission electron microscopy images of structures like the QD array.

Measurement set-up

We performed the measurements at the base temperature of a dilution refrigerator ($T \approx 10 \text{ mK}$). We sent low-frequency signals through cryogenic low-pass filters with a cutoff frequency of 65 kHz, while we applied pulsed signals through attenuated coaxial lines. Both signals were combined through bias T's at the level of the sample printed circuit board. The printed circuit board was made from 0.8-mm-thick RO4003C with an immersion silver finish. For readout, we used rf reflectometry applied on the ohmic contact of the device. We sent rf signals through attenuated coaxial lines to an LC resonator on the printed circuit board and arranged in a parallel configuration. The resonator had a coupling

capacitor (C_c), a 100-nm-thick NbTi superconducting spiral inductor (L) and the parasitic capacitance to ground (C_p), as shown in Fig. 1c. We drove the resonator at 512.25 MHz, which was the frequency of the system when G_s was well above the threshold. The reflected rf signal was then amplified at 4 K and room temperature, followed by quadrature demodulation, from which the amplitude and phase of the reflected signal were obtained (homodyne detection).

rf-cascade readout performance

The SNR of the interdot charge transition shown in Fig. 2b was determined by fitting the signal to an expression proportional to the quantum capacitance, which is proportional to $\partial^2 E / \partial \varepsilon^2$ (refs. 35,37),

$$V_{L,Q} \propto V_{L,Q}^0 - S_{L,Q} \frac{(2t_c)^3}{((\varepsilon - \varepsilon_0)^2 + (2t_c)^2)^{3/2}}, \quad (4)$$

where t_c is the tunnel-coupling, ε_0 is the detuning value of the centre of the peak, and $S_{L,Q}$ and $V_{L,Q}^0$ are the voltage signal and voltage offset of the phase and quadrature components of the measured rf response, respectively. The power SNR was determined by combining the measured in-phase and quadrature voltage signal components of the reflected rf signal,

$$\text{SNR} = \frac{S_I^2 + S_Q^2}{0.5(\sigma_I^2 + \sigma_Q^2)}, \quad (5)$$

where $S_{\text{rf},I(Q)}$ and $\sigma_{\text{rf},I(Q)}$ are indicated in Fig. 2b and represent the signal and the standard deviation in the background signal (away from zero detuning), respectively. Here we assume a white noise spectrum dominated by the first cryogenic amplification stage⁶⁰. In the measurements acquired throughout the text, the applied rf power was $P_{\text{rf}} = -88.5$ dBm, corresponding to a power SNR $= (1.7 \pm 0.1) \times 10^3$. The minimum integration time was determined using³⁵

$$\tau_{\text{min}} = \frac{N_{\text{avg}}}{2\Delta f \text{SNR}} \quad (6)$$

where $N_{\text{avg}} = 4,000$ is the number of averages used in the measurement, and $\Delta f = 1.53 f_{\text{LPF}}$ is the measurement bandwidth set by the low-pass filter cutoff frequency $f_{\text{LPF}} = 100$ kHz. Together, these two parameters give the noise-equivalent integration time $\tau_{\text{NE}} = 13$ ms for the measurement in Fig. 2b. Substituting the SNR into equation (6), we found the minimum integration time $\tau_{\text{min}} = 7.6 \pm 0.2$ μ s. In combination with the relaxation time T_1 extracted in Fig. 2e, the readout fidelity was calculated using the following expression³²:

$$\mathcal{F}_r = \frac{1}{2} \left[1 + \text{erf} \left(\sqrt{\frac{\tau_{\text{int}}}{8\tau_{\text{min}}}} \right) \exp \left(-\frac{\tau_{\text{int}}}{2T_1} \right) \right], \quad (7)$$

where τ_{int} is the integration time and $\text{erf}(x)$ is the Gaussian error function. The corresponding readout infidelity $1 - \mathcal{F}_r$ is shown in Fig. 2f.

We define the detuning fluctuations associated with the rf excitation to be given by³⁵

$$\delta \varepsilon_{\text{rms}}^{\text{rf}} = \frac{\alpha_{21} V_{\text{dev}}}{\sqrt{2}}, \quad (8)$$

where $\alpha_{21} = \alpha_{R,2} - \alpha_{R,1}$ and V_{dev} is the voltage excitation at the reservoir ohmic contact the from input rf signal V_{in} (ref. 61):

$$V_{\text{dev}} = \frac{2C_c Q_L V_{\text{in}}}{C_c + C_p}, \quad (9)$$

where $Q_L = 100$ is the loaded quality factor of the resonator depicted in Fig. 1c, and r.m.s. $V_{\text{in}} = 8.4$ μ V corresponding to input $P_{\text{rf}} = -88.5$ dBm. We then estimated an upper bound $\alpha_{21} \geq 0.01$ by rearranging equation

(1), assuming $\alpha_{R,ME} = 0.35 \pm 0.15$. The resulting rf-induced fluctuation in detuning was then $\delta \varepsilon_{\text{rms}}^{\text{rf}} \leq 2.7 \pm 0.6$ μ eV.

Control sequence and charge noise estimation

The pulse sequence implemented to demonstrate exchange control is as follows:

- (1) E: (E) mpty QD Q_1 by biasing the gate voltages such that the ground state is in the (0, 1) charge configuration, over a duration of 100 ns.
- (2) E-I: (I) nitialize the ground state $|S\rangle$ via an adiabatic ramp from the (0, 1) to the (0, 2) configuration, over a duration of 10 μ s.
- (3) I-S: (S) et a symmetric detuning point for applying subsequent ramps with a non-adiabatic pulse across the $|S\rangle - |T_-\rangle$ anticrossing to $\varepsilon = 0$, over 100 ns.
- (4) S-P: Initialize $|\downarrow\uparrow\rangle$ via a (P) lunge to where $J < \Delta E_z$ with an adiabatic ramp with respect to ΔE_z to $\varepsilon = 0.926$ meV over 250 ns.
- (5) P-J-P: Apply a non-adiabatic pulse to near zero detuning ε_j and back, where $J \gg \Delta E_z$, for variable duration τ_j .
- (6) P-M: Project the final state onto $|S\rangle$ or $|T_0\rangle$ for readout with a reverse adiabatic ramp to $\varepsilon = 0$.
- (7) M: Wait for a pre-measure delay of 6 μ s, before integrating, for a measurement time of 8 μ s.

The total duty cycle of the control sequence, $T_{\text{rep}} \approx 25$ μ s, provides the high-frequency bound f_{high} we integrate over to estimate S_0 , the power spectral density noise at 1 Hz. In combination with the total time used to acquire a trace of exchange oscillations, $T_M = 1/f_{\text{low}} = 0.3$ h, we can estimate S_0 from⁶²

$$\delta \varepsilon_{\text{rms}} = \sqrt{2 \int_{f_{\text{low}}}^{f_{\text{high}}} S_\varepsilon(f) df}, \quad (10)$$

where the power spectral density of charge noise has the functional form $S_\varepsilon(f) = S_0/f^\alpha$ with typical values of α ranging from 1 to 2. Considering the measured integrated charge noise ($\delta \varepsilon_{\text{rms}} = 5.4$ μ eV), we estimated upper and lower bounds of $\sqrt{S_0^{\alpha=1}} = 0.91$ μ eV/ $\sqrt{\text{Hz}}$ and $\sqrt{S_0^{\alpha=2}} = 0.12$ μ eV/ $\sqrt{\text{Hz}}$, respectively. This result is on par with that reported in planar MOS devices⁵⁵ and strained Ge wells (Ge/SiGe)⁶³ $\sqrt{S_0} = 0.6 \pm 0.3$ μ eV/ $\sqrt{\text{Hz}}$, as well as Si wells in Si/SiGe heterostructures $\sqrt{S_0} = 0.3$ μ eV/ $\sqrt{\text{Hz}}$ to 0.8 μ eV/ $\sqrt{\text{Hz}}$ (refs. 50,56).

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

J.F.C.-W. conducted the experiments and analysed the results presented in this work with input from R.C.C.L., M.A.F., M.F.G.-Z. and J.J.L.M. J.F.C.-W., M.A.F. and R.C.C.L. conducted the preliminary experiments. T.M. and G.A.O. developed the QD rf simulator described in Supplementary Section 4 informed by electrostatic modelling completed by J.W. T.M. performed and wrote about the simulations under the supervision of D.F.W. and M.F.G.-Z. F.E.v.H. characterized the superconducting resonator and carried out the experiments on other devices to validate the rf-cascade technique with support from J.F.C.-W. and M.F.G.-Z. S.M.P. designed the device under the supervision of M.A.F., M.F.G.-Z. and J.J.L.M. J.J. and S.K. fabricated the device under the supervision of B.G. N.J. maintained the experimental set-up. J.F.C.-W., M.F.G.-Z. and J.J.L.M. wrote the paper with input from R.C.C.L., M.A.F., N.J. and S.M.P. M.F.G.-Z. and J.J.L.M. conceived and oversaw the experiment.

Competing interests

Quantum Motion Technologies Limited has filed a patent application related to this work: EP23206749.6 (Europe) by J.F.C.-W., R.C.C.L., M.A.F. and M.F.G.-Z.

Additional information

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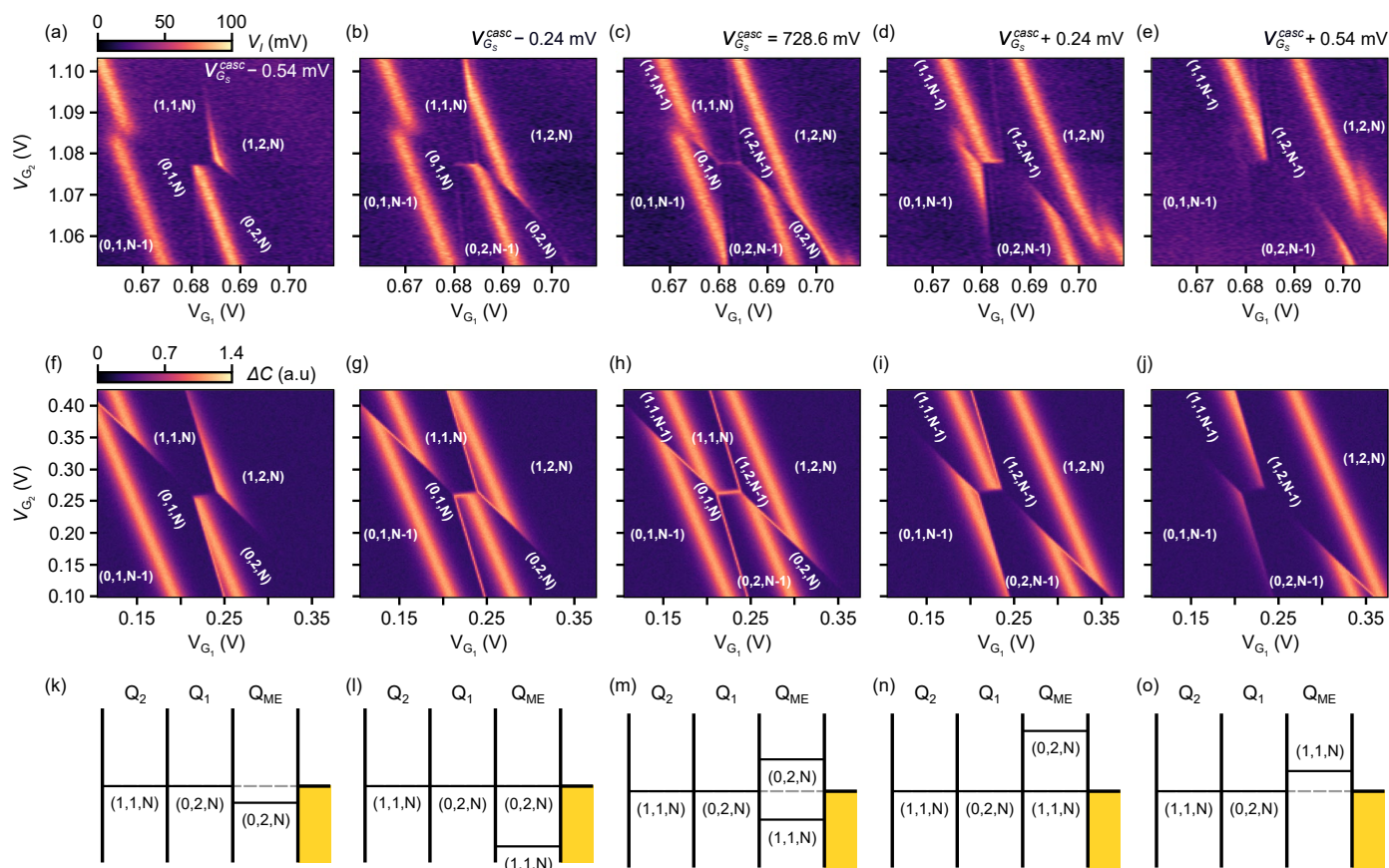
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Extended Data Fig. 1 | Tuning the radiofrequency driven electron cascade.

a-e, Charge stability diagrams as a function of the DQD gate voltages $V_{G_1} - V_{G_2}$. The multi-electron QD bias V_{G_2} is varied in each panel, defined with respect to $V_{G_2}^{\text{casc}}$, the bias where the conditions for cascade are observed, shown in panel **c**. This is the bias utilized in the main text of the manuscript. Similar data for additional devices can be

found in Supplementary Section 2. **f-j**, Simulated charge stability diagrams using the methods described in Supplementary Section 4. **k-o** Schematic depiction of the electrochemical levels for the corresponding bias conditions, arranged column-wise.